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SMALL BOAT HF RADAR CROSS SECTIONS

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Small Boat HF Radar Cross Sections

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The HF radar cross section of three small ocean-going craft were measured in full scale with the SEA ECHO radar. The measurements were made over a wide band of frequencies. Care was taken in the calibration of the system to insure accurate absolute values of cross section. This work was done in support of studies of the use of surface wave over-the-horizon radar for ocean range safety surveillance. The results demonstrated a severe fall-off of cross section for these typical craft at frequencies below 4 to 5 MHz.

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CONTENTS

SMALL BOAT HF RADAR CROSS SECTIONS

Introduction

Tactical Navy cruise-missile systems now currently in development are approaching a phase where the Pacific Missile Test Center and other ocean ranges must provide test-range facilities to cover greatly extended offshore distances. Instrumentation and range-safety surveillance requirements for such testing will reach to ranges which are well beyond the horizon-limited capability of ground-based microwave radar.

To fulfill the requirement for extended range safety coverage, PMTC has undertaken studies of possible approaches. These approaches are essentially limited to airborne systems and high-frequency over-the-horizon (OTH) radar. In the examination of the OTH approach, the Naval Research Laboratory conducted full-scale radar cross-section measurements of several small surface boats which are representative of the class of range-safety threat which would put maximum stress on the PMTC range safety function, namely fishing boats. In the language of the range safety function, "threat" describes the population of unwanted (if innocent) and uncooperative intruders for whom the military system test would be a hazard. In this sense the most serious threat class is the smallest, i.e., the least easily detected. In the PMTC studies, fishing craft were identified as the most difficult to detect of the threat population, in part because of their small size, and also because accurate prediction of their courses is more difficult than with heavy shipping.*

Most range safety criteria - and those of PMTC are no exception - are established with the objective of a very small probability of "incident" (the operative euphemism for injury to incidental craft or personnel in a weapon system test area). The guarantee of a small probability of incident requires an equivalent assurance of a high probability of detection by the range safety sensors. While for land ranges there may be considerable redundancy among various sensors, in the case of a remote large-area ocean coverage, such as that of PMTC, costs will most likely mandate a single system, e.g., HF OTH radar. In a careful balance between assured high detection probability and costs, all parameters must be known with accuracy and confidence.

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* An equally threatening set of intruders pointed out by NRL but not included in original studies is the population of small, low-flying fish-spotting aircraft.

Note: Manuscript submitted June 28, 1976.

Objectives

The Naval Research Laboratory was tasked in mid-1975 with the determination of values for the following:

- Radar cross section of fishing craft typical of the PMTC waters as a function of frequency.

- Noise and interference signal levels in the pertinent HF spectrum.

The frequency dependence of intruder radar cross section is important since the selection of a radar operating frequency (or frequencies) is critical to the selection of design parameters which will meet performance specifications and minimize cost. Some of these parameters are as follows.

1. The selection of a surface-wave propagation mode has the advantage that the choice of operating radio frequency is less restricted than it might be if a long-range (ionospheric) propagation mode were chosen. In either case, there are quantitative restrictions, however. For the ground-wave mode, propagation losses increase rapidly with increasing frequency, but target radar cross section will generally increase with increasing frequency. While the ionospheric propagation mode is not as subject to this difficulty, there are other, cost-related problems.

2. The sea itself as a source of backscatter tends, for a given sea state, to produce less clutter at low frequencies.*

3. For either mode there will be some minimum frequency at which the radar cross section of a given target will decrease rapidly with decreasing frequency, i.e., in the Rayleigh scattering region where the electrical dimensions of the target become small compared with the radar wavelength.

The SEA ECHO OTH radar facility at San Clemente Island is admirably suited for the purposes of measuring target cross section over a wide range of radar frequencies. SEA ECHO is deployed in close proximity to the PMTC test area and was designed with a facility for rapid acquisition of data over the full HF OTH radar spectrum. In earlier applications of the system, facilities and techniques were developed for accurate calibration of absolute values of radar cross section.

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* While a quantitative description of sea clutter as viewed with a coherent HF radar is complex, it is well understood: the generalization above is proper in this description.

Field Measurements

The SEA ECHO radar is located on the north shoreline of San Clemente Island with a scan sector lying between the azimuth of 300° and 340° (true). The antenna is electrically steered within this sector in 2-degree increments. Beam width is 2 degrees at approximately 15 MHz and above and is proportionately broader at lower frequencies. For the target cross-section measurements, the system was operated in the unchirped mode with a pulse length of 50 microseconds (15-km range gate). For the measurements, targets were operated at a range of approximately 22.5 km. The radar was run pulse-to-pulse at 25 frequencies, spaced logarithmically from 2.01 to 24.54 MHz. Data were processed for all frequencies in the form of Fourier transforms of 25 seconds of data (256 samples) and is presented as radar cross section in dB above a square meter (dBsm) vs. doppler frequency. Sea clutter as seen by a doppler radar appears in the processed output as two spectral lines spaced symmetrically around zero doppler. These lines represent the coherent cross section of approaching and receding ocean waves of wavelength exactly one-half of the radar wavelength. In order to provide an identifiable target signature which is clearly distinguishable from the clutter lines, the boat targets were run on courses radial to the radar and at speeds which separated their doppler velocity from that of the sea.

Cross-Section Calibration

A monopole calibration source was used in these measurements to provide a quantitative reference for the determination of absolute radar cross sections of the targets of interest. Figure 1 is a photograph of this monopole. It consists of a single vertical quarter-wavelength antenna of adjustable length mounted in a small aluminum rowboat. The antenna is grounded to the boat - hence to the water - by a coaxial RF switch. The periodic closure of this grounding switch is controlled by a crystal-oscillator, frequency-divider circuit whose rate can be chosen so as to produce pseudo-doppler signals in the radar signal processor output. When the monopole is situated in an appropriate radar spatial resolution cell, a predetermined and identifiable Doppler shift will be produced without the necessity for motion of the calibrator. The radar cross section of a tuned monopole is $\sigma_M = \lambda^2 G^2/4\pi$ where $G = 0.141$. The doppler signal from the switched monopole is distributed into sidebands. The effective cross section of each sideband is $\sigma_M = \lambda^2 G^2/4\pi^3$. Based on this value for absolute cross section, a quantitative value for the cross section of the test target - when passing close to the location of the calibrator - can be determined without a precise quantitative knowledge of the radar system parameters.

Extensive tests have been performed on the calibrator in the past, including measurements made with the carefully calibrated surface-wave system of the NRL MADRE radar. On the basis of these and other

extensive measurements made at San Clemente Island over the past three years, it is estimated that the monopole calibrator represents an intrinsic cross section whose accuracy is within ±1 dB. In use at sea, some slight modulation of the calibrator signal has been observed - possibly due to the lateral bending motion of the whip antenna. This modulation introduces possible errors of interpretation which slightly degrades the absolute accuracy obtainable. The consequences of this degradation are discussed in a later section.

The monopole calibrator's range of resonant radio frequency settings is from 6.7 to approximately 20 MHz, where the lower limit is determined by the maximum adjustment length of the antenna and the upper limit by an antenna length which begins to approach the vertical boat dimensions and/or surrounding ocean wave height. The monopole is still useful as a calibrator below 6.7 MHz, insofar as the nonresonant cross section is well understood in this region.

Nonresonant Monopole Cross Section

In past work the monopole has been used for cross-section calibration at the frequency for which it was adjusted to resonance: for measurements over the range of frequencies it was successively adjusted (i.e., the height of the antenna) to quarter-wave resonance, one frequency at a time.

In the measurements for PMTC, frequencies of interest extended down to approximately 2.0 MHz, a frequency for which the monopole, to be in quarter-wave resonance, would have had to be extended to an impractical length, i.e., higher than the 6.7-MHz limit imposed by the available whip antenna. Accordingly, the calibrator was utilized in these tests in both resonant and nonresonant modes. In the nonresonant regions, the cross-section behavior of a monopole is a somewhat complex function since it is proportional to the difference in cross section between an unswitched monopole and dipole. In the Rayleigh and resonance frequency region of the monopole, the dipole cross section is a very small value, so that the cross section of the switched monopole is just π^{-2} times the unswitched value as a function of frequency. In these tests the experimental monopole was simply tuned in length so that a comparison with target amplitude could always be made in the Rayleigh region of one of the tuned monopole settings.

Figure 2 is a plot of log of the cross section of an unswitched monopole tuned to a quarter-wavelength resonance of 10 MHz as a function of log frequency[1]. The cross section actually maximizes at slightly less than a quarter wavelength, i.e., 0.235, and exhibits an f^8-slope behavior in the Rayleigh region of scatter. The next resonance at $3\lambda/2$ is also shown in the figure. The solid line with f^{-2} slope is the locus of resonant monopole cross section as a function of frequency.

Also shown as a dashed line in Figure 2 is a plot of the expected cross section in the Rayleigh and resonance region for a switched resonant monopole as a function of frequency. A monopole tuned to 10.27 MHz is shown as an example.

The validity of the assumed off-resonant Rayleigh region monopole cross section was tested in the field by making simultaneous multi-frequency measurements of the monopole with the SEA ECHO radar and with the calibrator on station at a typical test range of approximately 22.5 km. With the radar sampling at all 25 frequencies, cross-section measurements were made with the monopole successively adjusted to resonance at several of the sample frequencies. The measured ratios of cross section, e.g., 6.95/8.18, 8.18/10.27 and 10.27/12.02 were compared with the theoretical prediction of King and Wu. Agreement of within 1-2 dB was found and the extrapolation accordingly was assumed to be appropriate.

Radar Calibration

As noted in the foregoing, the determination of target absolute cross section is based on the known characteristics of a calibrator placed in proximity to the test target. That is, quantitative radar and propagation characteristics (e.g., transmitted power, antenna gain, surface wave loss, etc.) were not invoked. An internal calibration capability is built into the SEA ECHO system, however, and a schedule for establishing absolute parameters is currently under way. During the PMTC measurement program in fact, an absolute calibration of the system was assayed with the monopole on a single frequency.

Test Targets

Cross sections of three targets were determined. These targets included two typical commercial fishing boats, chartered from southern California ports, and a Naval Undersea Center torpedo retrieval boat.

Figures 3, 4 and 5 are scaled in-board profile drawings of the three sample boats measured.

The BILL KETTNER is a 65-foot commercial fishing boat based in Long Beach which operates in coastal waters between Baja California and Oregon. The significant radar features are an HF communication antenna and two trolling booms which are stowed port and starboard in a vertical position. These booms are wood but a series of metal trolling lines are attached along their length and hang vertically in the stowed position.

The SOUTHERN COMFORT II is a 42-foot, day-party boat operating out of Newport Beach. While it is equipped with an HF antenna, the

HF gear is out of use and it is believed that the antenna is not grounded. (Communications are accomplished with VHF equipment.)

The Naval Undersea Center TRB-10 is a Navy craft designed for the recovery of test and exercise torpedos. It is also used extensively for utility work. TRB-10 and its sister craft, TRB-4, were used extensively as a target for earlier NRL work with the SEA ECHO system and was included for convenient comparison with this earlier data. TRB-10 is 65 feet overall. All antennas, including HF, are actively used. The aft-deck structure shown in the figure is a hydraulic lifting boom shown in stowed position.

Test Procedure

The physical positioning of the test targets and monopole was accomplished in the initial measurement series with aid of a Naval Undersea Center instrumentation radar facility on San Clemente Island. To insure position accuracies of the order of a few meters, a radar transponder was used on the operating craft. In those measurements it was found that the SEA ECHO radar could detect the target in three adjacent azimuthal beams, and thereby keep it centered within the middle beam, so that the instrumentation radar was not used in the later measurement series.

Prior to a measurement, the test target - with the monopole boat stowed on board - was vectored to a convenient SEA ECHO resolution cell either by the NUC radar or by SEA ECHO. When on station the monopole was deployed and secured against wind drift with a drogue anchor. The position was also marked with a man-overboard buoy, also provided with a drogue. Test runs were made on headings radial to and from the radar over courses of about one mile, centered at the monopole. Passage of the monopole was marked in time by a VHF voice communication link with the radar. Some wind drift of the monopole was experienced as marked by the MOB buoy and some current drift as measured by both shore radars. However by keeping the target course in proximity to the monopole, consistency was maintained in their comparative cross sections.

The SEA ECHO antenna produces a 2° beam width at 15 MHz and above and proportionately broader at lower frequencies. A 50-microsecond range resolution was used for these tests.

Sea and wind conditions were fortuitously mild for all tests. Wind velocities were estimated at five knots or less, swell at one to two feet maximum and wind waves were essentially in the capillary class. The surface current was variable but, at most, approximately 0.3 kt from the northwest. The measurements were conducted at a range of approximately 22.5 km from the radar.

Results

Values of radar cross section in dBsm as a function of frequency are presented in Figures 6 through 10. The data are presented separately for fore and aft aspects, i.e., with the target approaching and receding from the radar. (At times during the operations - e.g., while retrieving the monopole boat - the test target at dead stop was observed by the radar: while the target was clearly detectable, no attempt has been made with these data to evaluate the absolute cross section.)

The plots present measured values of target cross section as determined by comparison with the monopole calibrator signal interrupted both at resonance and off resonance. The numerical values associated with the identifying symbols represent the resonant frequency for which the monopole was adjusted in producing that data point.

The smooth curve is a hand-fit to the data points and represents an estimated value of cross section as a function of frequency which would be suitable for use in the design of an operational range-safety radar.

In processing the radar spectral data, temporal fluctuation of the signal from the monopole of the order of ±2 dB appeared during some target runs. These fluctuations appear to be associated with the calibrator alone since the target signal remained quite steady (i.e., fluctuation of less than one dB) during the same recording periods. At sea, even under moderate wave conditions, the monopole boat experiences sufficient rolling motion to cause significant whipping or bending of the slender monopole antenna, particularly when extended to or nearly to its maximum height. At full extension the off-axis movement of the top end of the antenna may be as much as ten percent of its length. This motion may induce a doppler modulation of sufficient magnitude to spread the measured signal out of the processor doppler resolution bin to some extent. With this possibility in mind, the data which are presented were based on the maximum monopole signal, chosen from among several processing intervals during the target passage of the monopole.

Discussion

The variability of cross section of the BILL KETTNER appears to reflect the contribution of several significant radar scatters. There appear to be at least three maxima. It is interesting to note by reference to the scaled profile (Figure 4) that the heights above the waterline of (a) the HF antenna, (b) the marine radar antenna (over the wheelhouse) and (c) the smokestack agree quite closely with the resonant wavelengths of these maxima. There also appears to be some difference in cross-section profile between the front and aft aspects

of the boat. This effect may possibly be due to resonant interactions between the radar-significant structures and their relative phase-delay along the line of sight.

In the case of TRB-10, some structure can also be seen in the cross-section profile although it is not as prominent as with the BILL KETTNER. This might be expected in view of the more broadband RF nature of the TRB prominences.

The SOUTHERN COMFORT II shows the characteristics of a bulk reflector rather than one with resonant characteristics. It seems clear that the HF antenna, which had long been out of service, was not grounded, hence not playing a significant role in the overall cross section.

In summation, several generalizations are reasonable:

1. A small surface craft whose highest vertical projection is an electrically-connected structure will produce a back-scatter which is closely representative of that of a monopole of the same height; multiple structures will produce additive effects.

2. Small craft without significant vertical structures will demonstrate small cross sections and be the most difficult to detect.

3. Based upon the three targets represented in this work, target cross sections for the largest fishing craft begin falling off rapidly in the 5 to 7 MHz region, and the smallest boats' cross section will exhibit this behavior at even higher frequencies. However, the sea clutter cross section falls off in this lower range of radar frequencies as well, although still being a function of sea state. Since target detections under low external noise conditions would depend upon the signal to clutter ratios encountered, the choice of a range of operating frequencies in the design of a range safety radar is not an obvious one at this time.

Finally, and as a matter of interest to other Navy users, it is interesting to speculate that on the evidence of the BILL KETTNER as representative of larger vessels with complex superstructures, a multi-frequency OTH radar might be capable of performing target classification given an adequate catalogue of HF radar cross-section profiles.

REFERENCES

1. R.W.P. King, T.T. Wu, Scattering and Diffraction of Waves, Harvard University Press, Cambridge, Massachusetts, 1959.

Fig. 1 — A photograph of the resonant test monopole which was used as calibration for the cross section measurements

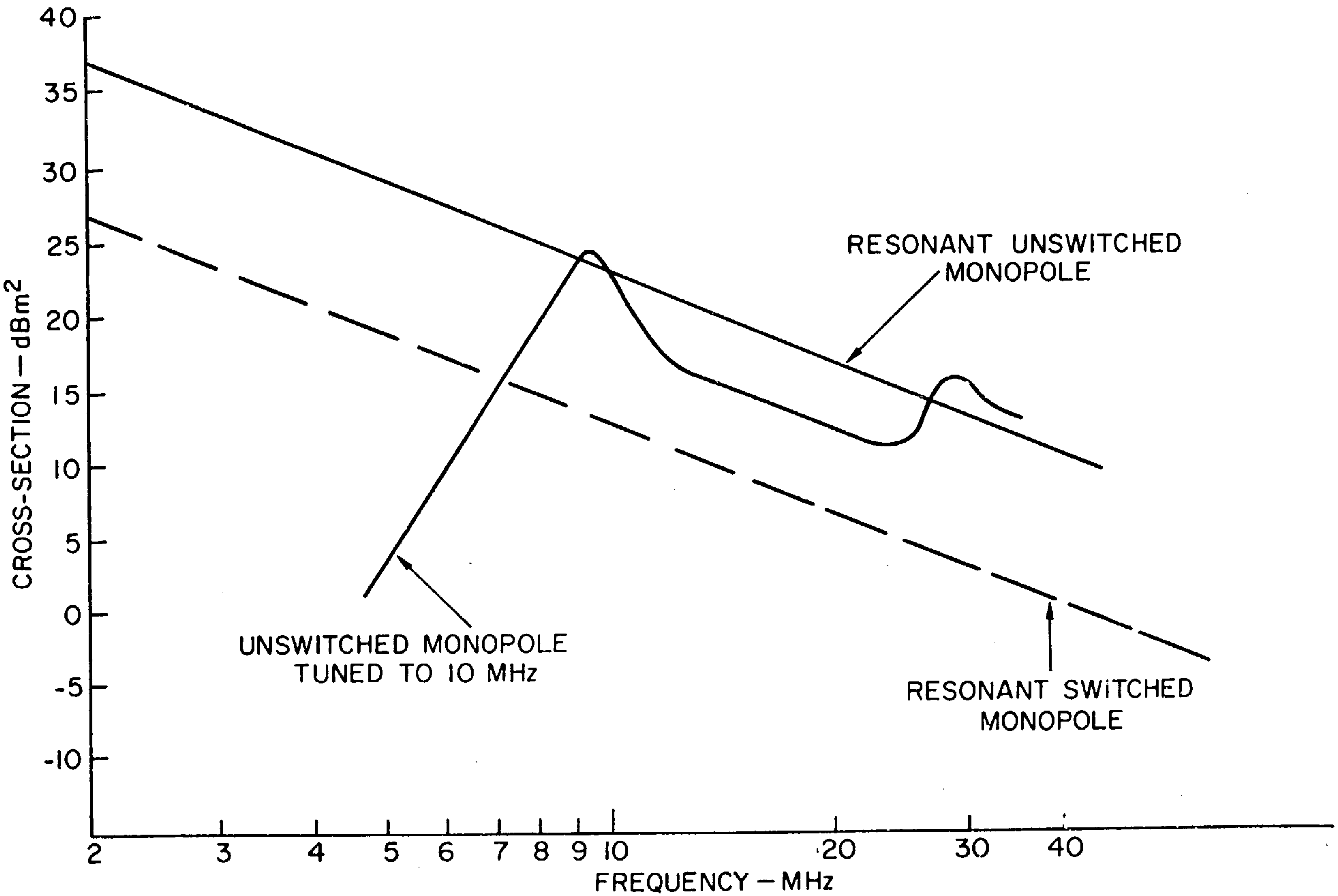


Fig. 2 — The twin peaked curve is a plot of the frequency dependence of the cross section of a single monopole tuned to 10 MHz. The solid straight line is the locus of resonant values of monopoles from 2 to 40 MHz, with the 10 MHz curve crossing being a single point on the locus. The dashed line is a similar locus, but for the cross section of one of a pair of sidebands which appear when the monopole is switched.

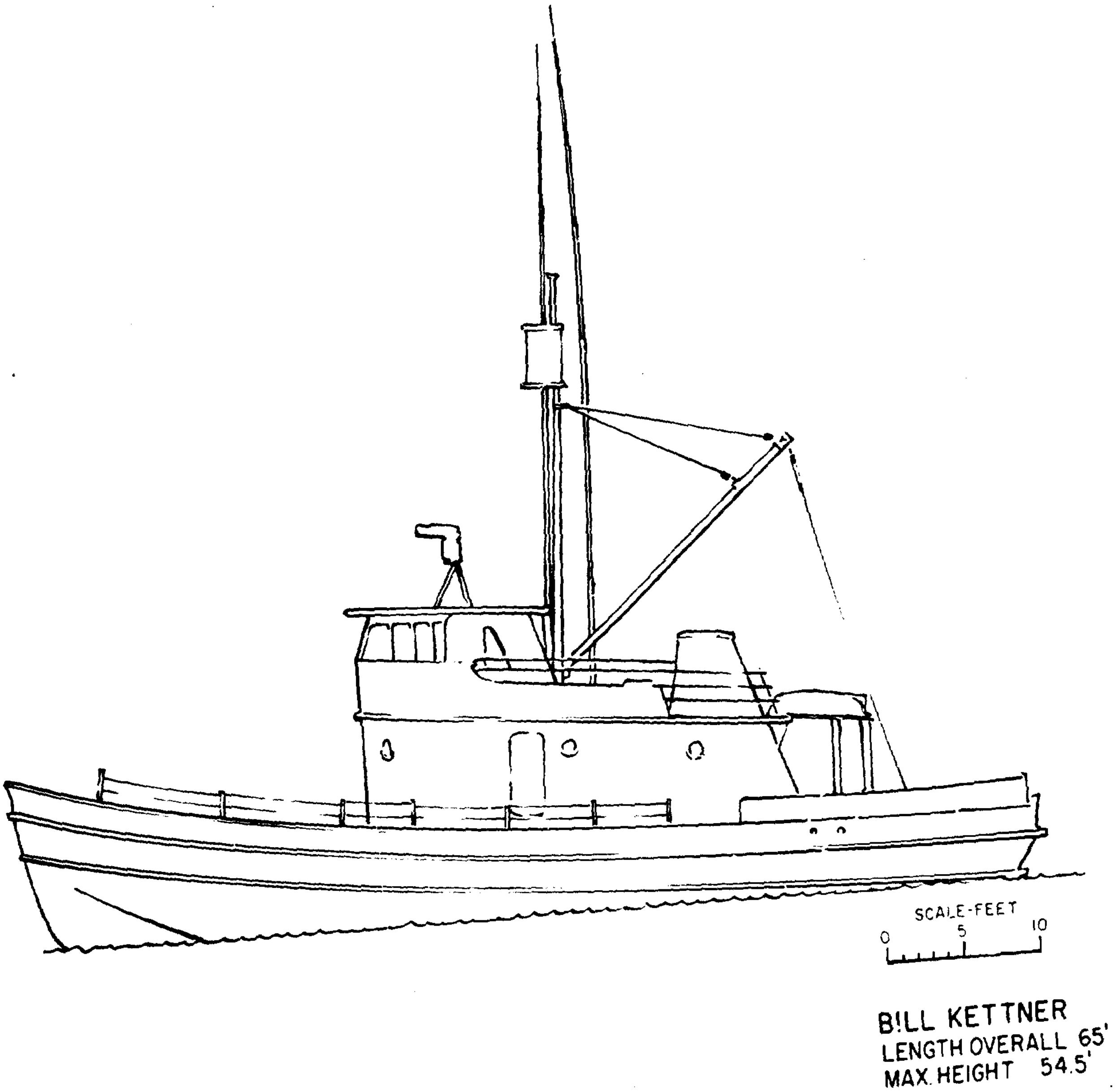
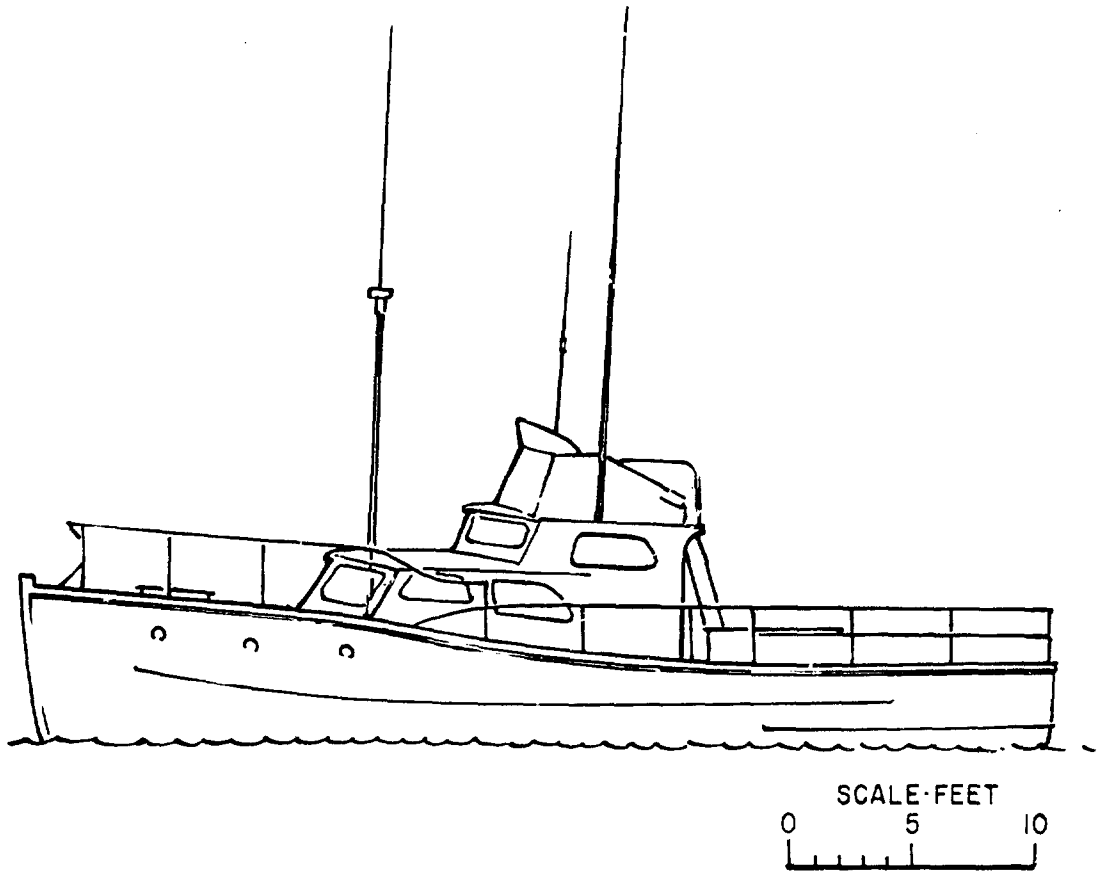


Fig. 3 — A line drawing to scale of the largest fishing boat measured in these tests



SOUTHERN COMFORT II
LENGTH OVERALL 42'
MAX. HEIGHT 29.5'

Fig. 4 — A line drawing to scale of a representative small fishing boat which was measured in these tests

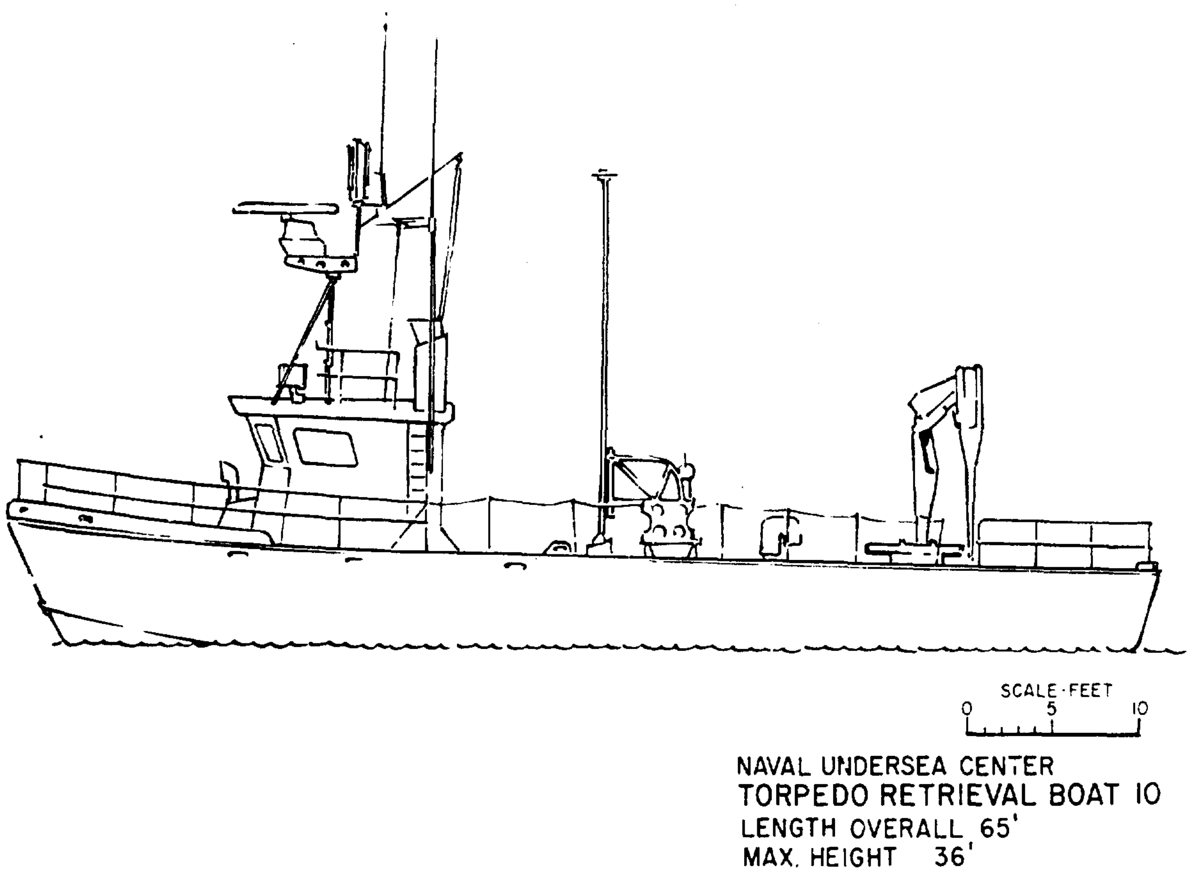


Fig. 5 — A line drawing to scale of the Torpedo Retrieval Boat which was measured in these tests

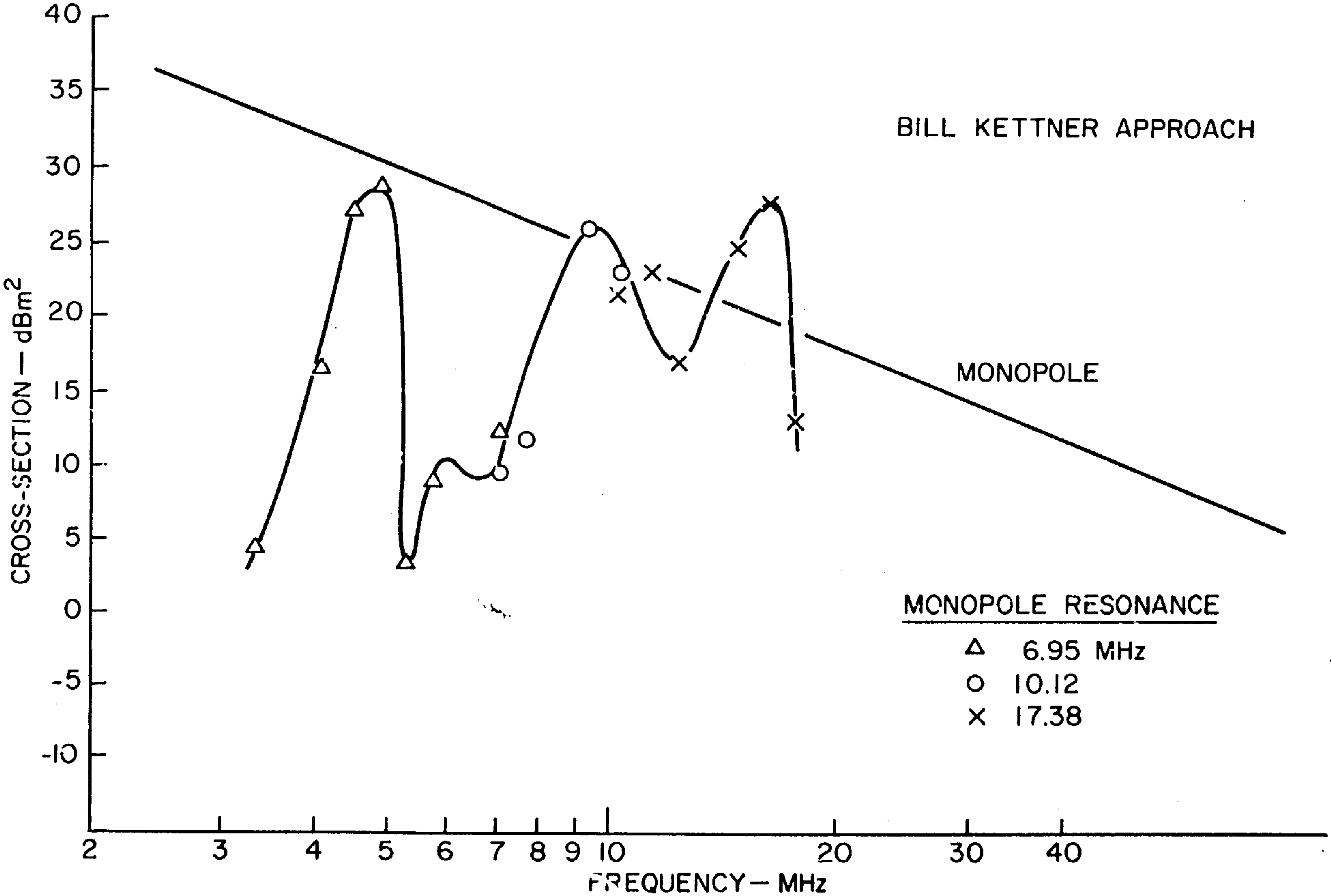


Fig. 6 — The cross section as a function of radar frequency of the 65-foot fishing boat as measured from a bow-on view. Note the resonant minimum near 5 MHz and the multiple resonant series of peaks due to the complex vertical structures aboard ship.

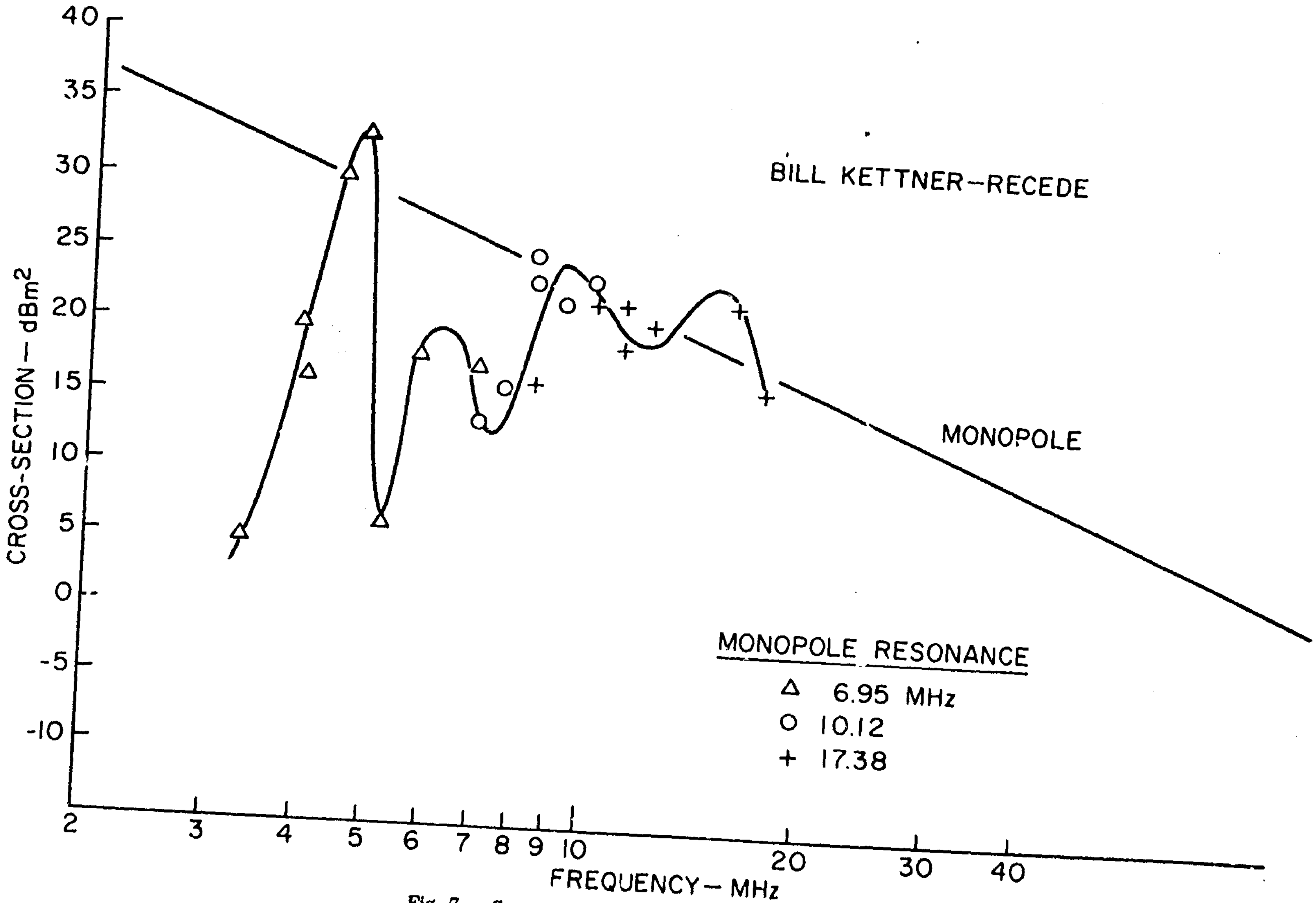


Fig. 7 — Same as Fig. 6, but for stern-on view

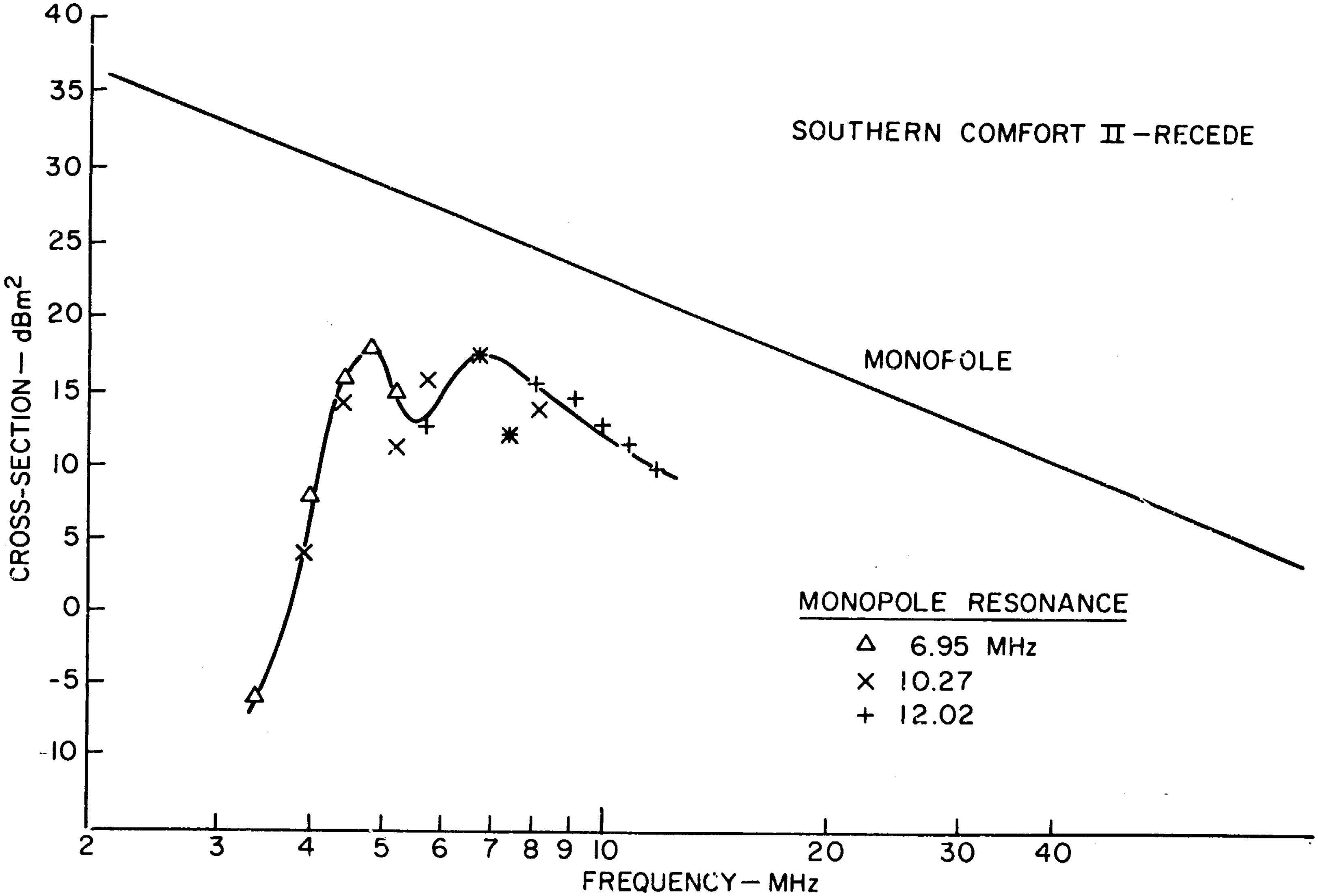


Fig. 8 — The cross section as a function of radar frequency of the 42-foot fishing boat as measured from a stern-on view. Bow-on view is essentially identical.

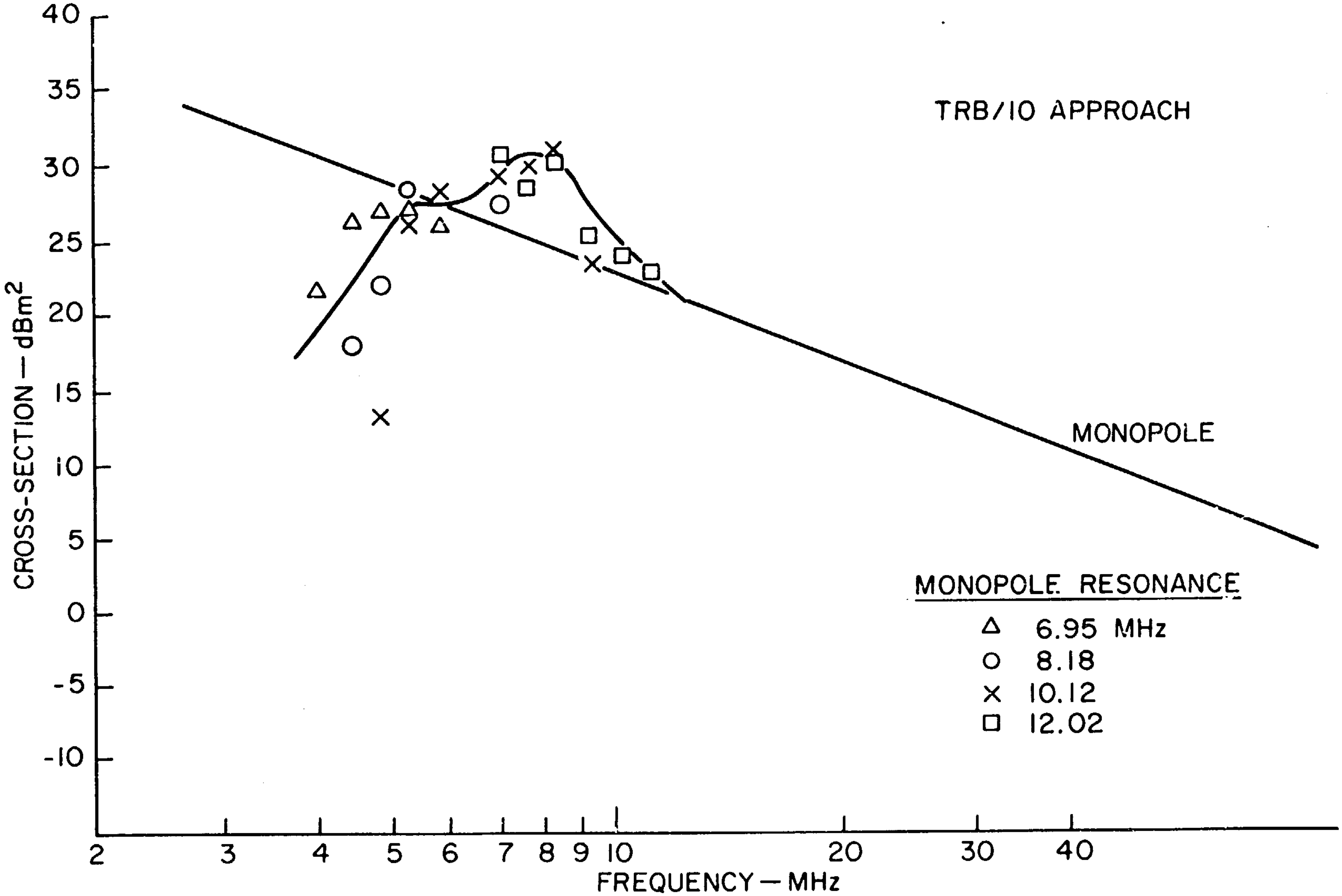


Fig. 9 — The cross section as a function of radar frequency of the TRB for stern-on view

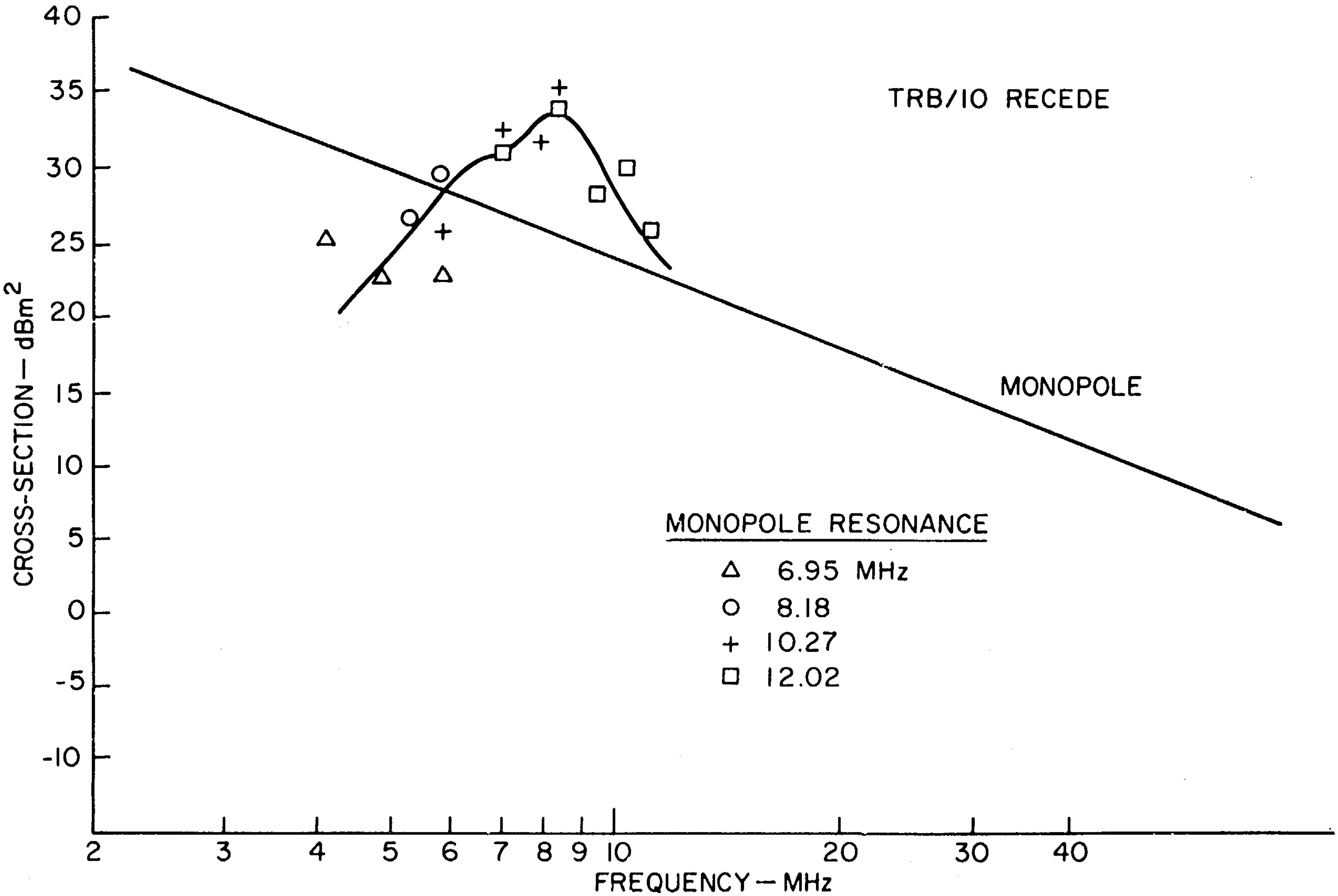


Fig. 10 — Same as Fig. 9, but for bow-cn view